Quantum Numbers and Decay Widths of the $\psi(3095)$†

A. M. Boyarski, M. Breidenbach, F. Bulos, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,* R. R. Larsen, D. Lüke,‡ V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, P. Rapidis, B. Richter, R. F. Schwitters, W. Tanenbaum, and F. Vannucci§
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. D. Briggs, W. Chinowsky, C. E. Friedberg, G. Golhaber, J. A. Kadyk, A. M. Litke, B. A. Lulu, F. M. Pierre,‖ B. Sadoulet, G. H. Trilling, J. S. Whitaker, F. Winkelmann, and J. E. Wiss
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 7 April 1975)

We present cross sections for $e^+e^- \to$ hadrons, e^+e^-, and $\mu^+\mu^-$ near 3095 MeV. The $\psi(3095)$ resonance is established as having an assignment $J^{PC}=1^{--}$. The mass is 3095 ± 4 MeV. The partial width to electrons is $\Gamma_e = 4.8 \pm 0.6$ keV and the total width $\Gamma = 69 \pm 15$ keV. Total rates and interference measurements for the lepton channels are in accord with μ-e universality.

Following the discovery of the $\psi(3095)$[1,2] and the $\psi(3684)$,[3] we made extensive measurements of the cross sections for $e^+e^- \to$ hadrons, e^+e^-, and $\mu^+\mu^-$ as a function of energy near the resonances, using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-LBL) solenoidal detector at SPEAR. This Letter makes use of these new data to deduce the quantum numbers, the mass, the total width, and the partial decay widths for the $\psi(3095)$. We assume that the ψ is a unique state.

The trigger employed, the event selection criteria, and the calculation of detection efficiency for multihadron states are described by Augustin *et al.*[4,5] All cross sections were normalized using luminosity monitors which measure small-angle (25 mrad) Bhabha scattering. Backgrounds were of the order of 0.01% to 0.1% and have been neglected. Figure 1(a) shows the total cross section for hadron production versus center-of-mass energy E. We have assumed that there are no unobserved modes, such as totally neutral. Because the observed full width at half-maximum of 2.6 MeV is compatible with that expected from the energy spread in the storage ring, the width of the resonance must be significantly smaller. Figures 1(b) and 1(c) show the corresponding cross sections for the $\mu^+\mu^-$ and e^+e^- final states,[6] *in the angular region* $|\cos\theta| < 0.6$, where θ is the angle between the outgoing positive lepton and the incident positron. The errors shown include both statistical errors and systematic errors due to energy-setting errors (i.e., reproducibility) and point-to-point normalization errors.

The data of Fig. 1 were fitted simultaneously to obtain the mass m, and the partial widths Γ_e,

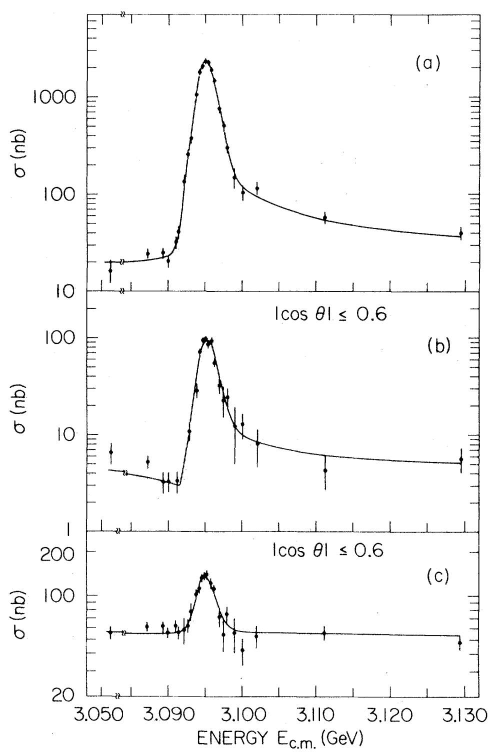

FIG. 1. (a) The total cross section for $e^+e^- \to$ hadrons versus center-of-mass energy. Errors given include systematics. The curve shows the expected cross section using the results in the table. (b), (c) The cross section for $e^+e^- \to \mu^+\mu^-$ and e^+e^-, respectively, versus energy integrated over the range $|\cos\theta| < 0.6$.

Γ_μ, and Γ_h to electrons, muons, and hadrons, respectively. We assume that the total width is $\Gamma = \Gamma_e + \Gamma_\mu + \Gamma_h$. The fit folded the Gaussian beam resolution function with radiative effects[7] and a Breit-Wigner cross section. We assumed an angular distribution of $1+\cos^2\theta$ for the leptonic decays and $J=1$ (justified in later discussion). The partial widths have a simple relation to the observed cross sections for any channel "c":

$$\int \sigma_c \, dE = \frac{2\pi^2(2J+1)}{m^2} \frac{\Gamma_e \Gamma_c}{\Gamma}, \quad (1)$$

where σ_c is the Breit-Wigner cross section for $e^+e^- \to \psi \to c$, and Γ_c is the partial width to the channel c. Such integrations, with appropriate radiative corrections, gave results in agreement with the fit.

The results[8,9] of the fit are given in Table I, with errors which principally reflect our systematic uncertainties. These include energy setting errors of ±100 keV, ±3% for errors in overall normalization, and ±15% for uncertainties in the detection efficiency of the hadron channel. Γ_e and Γ_μ are in good agreement, as expected for μ-e universality. $\Gamma_{\gamma h}$ is the partial width assuming $e^+e^- \to \gamma \to \psi \to \gamma \to$ hadrons; it is included in Γ_h. $\Gamma_{\gamma h}$ is derived from the relation $\Gamma_{\gamma h} = \Gamma_\mu \sigma_h(\text{nonresonant})/\sigma_\mu(\text{nonresonant})$, which assumes that the leptons couple to ψ only via photons. The nonresonant cross sections are obtained from Refs. 4 and 5. Since $\Gamma_{\gamma h} < \Gamma_h$, ψ must have direct coupling to hadrons.

The determination of the quantum numbers J^{PC} for the $\psi(3095)$ is made by a study of interference between resonance and quantum electrodynamic (QED) amplitudes and by examination of the angular distribution of leptons from ψ decays. Interference is most easily studied in the $\mu^+\mu^-$ channel because a resonant amplitude sharing the quantum numbers of the photon should show strong interference with the known s-channel QED amplitude.[10] To exhibit interference effects, it is convenient to use the ratio of $\mu^+\mu^-$ to e^+e^- yields seen in the detector, thereby minimizing systematic errors due to normalization. This ratio for the detected angular range $|\cos\theta| < 0.6$ is shown in Fig. 2(a). Also shown are curves representing no interference, e.g., $J=0$, and maximum interference, i.e., a pure $J^{PC}=1^{--}$ state. The cross-section integrals obtained in the previous section fix the parameters for the curve. In the region 3.087 to 3.093 GeV we observe 85 μ pairs and 1497 e pairs. Given that number of e pairs we should have observed 114 μ pairs on the hypothesis of no interference and 78 μ pairs for full interference. The data agree with the maximum interference prediction and disagree with the hypothesis of no interference by 2.7 standard deviations. Because the detector is symmetric in space and with respect to charge, and sums over spins, the observation of interference unambiguously selects the assignment −1 for both parity and charge conjugation of the $\psi(3095)$, on the assumption that the resonance is an eigenstate of P and C.

TABLE I. Properties of $\psi(3095)$.

Mass	3.095 ± 0.004 GeV
J^{PC}	1^{--}
Γ_e	4.8 ± 0.6 keV
Γ_μ	4.8 ± 0.6 keV
Γ_h	59 ± 14 keV
$\Gamma_{\gamma h}$	12 ± 2 keV
Γ	69 ± 15 keV
Γ_e/Γ	0.069 ± 0.009
Γ_μ/Γ	0.069 ± 0.009
Γ_h/Γ	0.86 ± 0.02
Γ_μ/Γ_e	1.00 ± 0.05

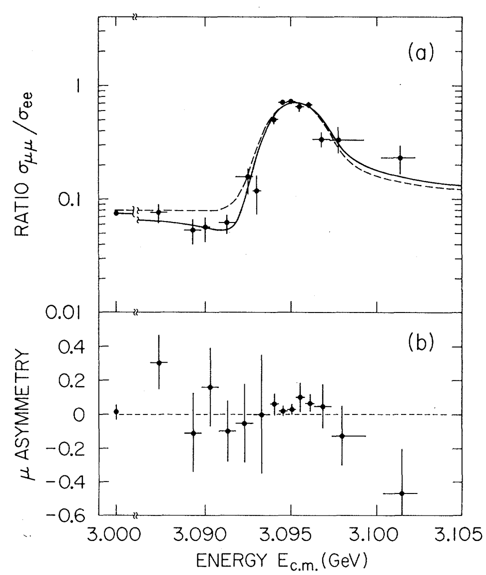

FIG. 2. (a) The ratio of μ-pair yield to e-pair yield versus center-of-mass energy. The dashed line gives the expected ratio for no interference while the solid line gives the expected ratio for full interference. Only statistical errors are shown. Systematic errors are 1–2%. (b) The front-back asymmetry of μ pairs versus center-of-mass energy; errors are statistical. Systematic errors are 1–2%.

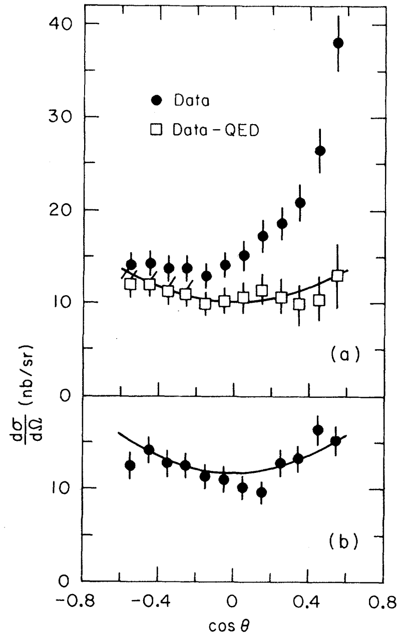

FIG. 3. (a) The angular distribution of electron pairs for the energy range 3.0944 to 3.0956 GeV. Also shown is the result of subtracting QED to obtain the resonance angular distribution. (b) The angular distribution of μ pairs in the same energy range. The lines represent $1+\cos^2\theta$.

Because of the limited angular acceptance of the detector, one cannot conclude just from the interference that $\psi(3095)$ has spin 1 without more detailed arguments. Since the QED amplitudes vanish for zero helicity in either the initial or the final state, only resonance amplitudes having nonzero helicity may interfere. It follows that spin 0 is excluded. Parity conservation relates those four helicity amplitudes to a single independent amplitude. Since the QED amplitude is real, the interference is determined by the real part of the one independent resonance helicity amplitude times an angular overlap integral over the range $|\cos\theta| < 0.6$. The integral is completely determined by the value of J. T invariance, μ-e universality, unitarity, and causality specify the sign of the real part of the resonance amplitude below resonance. Spin 1 produces a *destructive* interference while spins 2 and 3 will both produce a *constructive* interference below resonance.[11] Thus spins 2 and 3 are rejected by having confidence levels even less than that of spin 0. Finally, spins greater than 3 may be excluded because their overlap integral is negligible.

The assumption that the resonance is an eigenstate of P and C may be tested by studying the front-back asymmetry in the leptonic decays. The measured asymmetry for μ pairs versus energy,[12] shown in Fig. 2(b), has at resonance a value of 0.02 ± 0.03, which indicates no significant parity or charge-conjugation noninvariance. For comparison, data at 3.0 GeV are also shown.[4] The asymmetry is consistent with zero between 3.087 and 3.102 GeV, which argues against the ψ being a degenerate mixture of states of opposite parity.

The angular distributions of e pairs and μ pairs are shown in Fig. 3. Both distributions, after subtraction of the QED contributions, are consistent with the angular distribution $1+\cos^2\theta$ expected for a simple 1^{--} state populating only helicity ± 1, but are inconsistent with 2^{--} and 3^{--} states populating the same helicity states.[13] Thus, the angular distributions confirm the interference results, $J^{PC} = 1^{--}$.

We should like to thank numerous members of the SLAC Theory Group and Professor J. D. Jackson for informative discussions.

---

†Work supported by the Energy Research and Development Administration.

*Permanent address: Laboratoire de l'Accélérateur Linéaire, Centre d'Orsay de l'Université de Paris, 91 Orsay, France.

‡Fellow of Deutsche Forschungsgemeinschaft.

§Permanent address: Institut de Physique Nucléaire, Orsay, France.

‖Permanent address: Centre d'Etudes Nucléaires de Saclay, Saclay, France.

[1]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[2]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[3]G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[6]As pointed out in Ref. 1, we cannot exclude the possibility of some small hadron contamination in our μ sample.

[7]Cross sections shown have not been corrected for radiative effects. The overall radiative corrections to the partial widths are ~30% and are part of the fitting procedure. For discussion of radiative corrections cf. Y. S. Tsai, SLAC Report No. SLAC-PUB-1515 (unpublished); D. R. Yennie, Phys. Rev. Lett. 34, 239 (1975).

[8]The mass quoted differs from that of Ref. 1 because of recalibration of the storage ring's absolute energy. The uncertainty quoted is an estimate of systematic errors in this new calibration.

[9]Results related to these have been published. The authors have not applied radiative corrections. W. W. Ash *et al.*, Lett. Nuovo Cimento 11, 705 (1974); R. Baldini Celio *et al.*, Lett. Nuovo Cimento 11, 711 (1974);

G. Barbiellini *et al.*, Lett. Nuovo Cimento 11, 718 (1974); W. Braunschweig *et al.*, Phys. Lett. 53B, 393 (1974).

[10]Most of the QED cross section for $e^+e^- \rightarrow e^+e^-$ in the range $|\cos\theta| < 0.6$ is due to spacelike momentum transfer; thus interference in the electron channel is much smaller than in the μ channel (and of opposite sign, assuming μ-e universality).

[11]If the signs of the e coupling and μ coupling to ψ are different, the sign of the interference would be reversed. Considerations of angular distributions in the next section will exclude $J = 2$ or 3 and thus exclude a sign difference.

[12]Because of the large subtraction of QED necessary for electrons, the accuracy of the μ asymmetry is much superior to that of the electrons.

[13]Consideration of P and C invariance excludes zero-helicity amplitudes for a 2^{--} state. No such selection rule exists for a 3^{--} state, but helicity-1 amplitudes must be dominant to observe large interference.

ERRATUM

RESONANT X-RAY RAMAN SCATTERING. Yigal B. Bannett and Isaac Freund [Phys. Rev. Lett. 34, 372 (1975)].

The following acknowledgement should be appended: This research was supported by a grant from the United States–Israel Binational Science Foundation (BSF), Jerusalem, Israel.